PHOTONIC CRYSTALS AND LIGHT LOCALIZATION

NATO Advanced Study Institute
June 19-30, 2000
Crete, Greece

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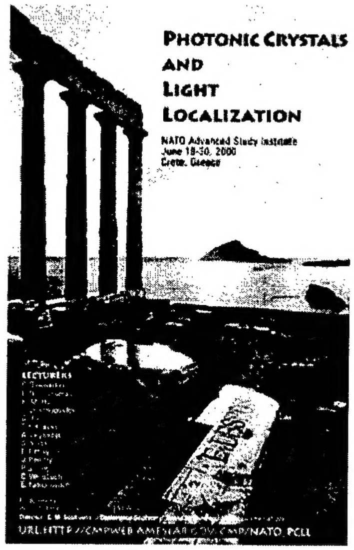
Limin Hersonissou, Crete, Greece



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NATO Advanced Study Institute
Photonic Crystals and Light Localization
Conference Program
June 18-30, 2000
Creta Maris Hotel
Limin Hersonnisou, Crete, Greece

All sessions will be held in the Creta Maris Hotel Conference Room. The Lectures will have 50 minutes for presentations and 10 minutes for discussion. The Talks will have 25 minutes for presentation and 5 minutes for discussion. The Posters will be displayed during two evening sessions. The poster presenter will be allowed to show one (1) view-graph, which is most representative of the poster to pique the interest of the audience.

Sunday, June 18, 2000

19:30-21:30	Welcoming Party at the Creta Maris Hotel

Monday, June 19, 2000

8:30	Registration
9:30	Opening and Welcoming Remarks

Morning Session	**Chairperson: E. N. Economou**
10:00	**Lecture**: J. D. Joannopoulos, Massachusetts Institute of Technology, *The Magical World of Photonic Crystals: I*
11:00	Coffee Break
11:30	**Lecture**: A. Lagendijk, University of Amsterdam, *Localization of Light I*
12:30	**Lecture**: J. Pendry, Imperial College, *Computing the Response of Structured Metals to Light*
13:30	Lunch and Discussions

Evening Session	**Chairperson: S. John**
17:30	**Lecture**: S. Lin, Sandia National Laboratory, *Microfabrication of 2d and 3d Photonic Crystals: I*
18:30	**Panel Discussion**: *Photonic Band Gaps*
19:30	End of Session

Tuesday, June 20, 2000

Morning Session	**Chairperson: A. Lagendijk**
9:00	**Lecture**: J. D. Joannopoulos, Massachusetts Institute of Technology, *The Magical World of Photonic Crystals: II*
10:00	**Lecture**: S. John, Toronto, *A Theoretical Roadmap for 3-d Photonic Band Gap Materials and Their Uses: I*
11:00	Coffee Break
11:30	**Lecture**: E. Ozbay, Bilkent University, *Physics and Applications of Photonic Crystals*
12:30	**Lecture**: S. Noda, Kyoto, *Semiconductor Photonic Crystals*
13:30	Lunch and Discussions
Evening Session	**Chairperson: Kurt Busch**
17:30	Session I: **Oral Presentation of the Posters**
18:00 - 19:30	**Posters**

Wednesday, June 21, 2000

Morning Session	**Chairperson: J. D. Joannopoulos**
9:00	**Lecture**: J. Pendry, Imperial College, *Intense Focusing of Light Using Metals*
10:00	**Lecture**: S. John, Toronto, *A Theoretical Roadmap for 3-D Photonic Band Gap Materials and Their Uses: II*
11:00	Coffee Break
11:30	**Lecture**: E. N. Economou, Research Center of Crete, *Elastic Waves in Periodic Composite Material: I*
12:30	**Talk**: C. T. Chan, Hong Kong, *Photonic Crystals From Metal-coated Spheres*
13:30	Lunch and Discussions
Evening Session	**Chairperson: D. A. Papaconstantopoulos**
17:30	**Lecture:** E. N. Economou, Research Center of Crete, *Elastic Waves in Periodic Composite Materials: II*
18:00	**Talk:** J. Page, University of Manitoba, *Acoustic Band Gap Materials*
18:30	**Talk:** F. J. Garcia-Vidal, University of Madrid, *Surface Plasmons of Lamella Metallic Gratings*
19:00	**Talk:** D. R. Smith, University of California, San Diego, *Left-handed Materials*
19:45	End of the Session

Thursday, June 22, 2000

Morning Session	**Chairperson: J. Pendry**
9:00	**Lecture**: Ad Lagendijk, University of Amsterdam, *Random Lasers*
10:00	**Talk:** H. Cao, Northwestern University, *Localization of Laser Light in Active Random Media*
11:00	Coffee Break
11:30	**Talk**: Z. Vardeny, University of Utah, *Random and Distributed Feedback Lasing in Opal PhotonicCrystals*
12:00	**Lecture**: C. M. Soukoulis, Ames Laboratory, Iowa State University, *Theory and Simulation of Random Lasers*
13:00	**Talk**: J. P. Woerdman, Leiden University, *Special Resonators for Random and Fractal Lasers*
13:30	Lunch and Discussions
Evening Session	**Chairperson: K. Asakawa**
17:30	**Talk**: S. Lin, Sandia National Laboratory, *Microfabrication of 2d and 3d Photonic Crystals: II*
18:00	**Talk:** T. Baba, Yokohama National University, *Light Propagation Characteristics in Defect Waveguides in a Photonic Crystal Slab*
18:30	**Talk**: D. C. Allan, Corning Incorporated, *Photonic Band Gap Fibers for Real World Applications*
19:00	**Talk:** R. E. Slusher, Lucent Technology—Bell Laboratories, *Symmetry, Laser Action, and Output Coupling in 2d Photonic Crystals*
19:30	End of the Session

Friday, June 23, 2000

Morning Session	**Chairperson: D. J. Norris**
9:00	**Lecture**: W. Vos, University of Amsterdam, *Strong Interaction Between Light and Photonic Crystals Made Using Self-Assembly*
10:00	**Lecture**: K. Busch, University of Karlsruhe, *Tunable Photonic Crystals*
11:00	Coffee Break
11:30	**Talk**: F. Meseguer, University of Valencia, *Inverse Opals Fabrication*
12:00	**Talk**: A. van Blaaderen, Ultrech University, *Manipulating Colloidal Crystallization for Photonic Applications*
12:30	**Talk**: S. G. Romanov, University of Wuppertal, *Light Manipulation of 3d Templated Photonic Crystals*
13:00	**Talk**: A.Polman, FOM, Amsterdam, *Fabrication and Characterization of Silicon-based Photonic Band Gap Materials*
13:30	Lunch and Discussions
Evening Session	**Chairperson: A. Polman**
17:30	**Talk**: K. Asakawa, The Femtosecond Technology Research Association (FESTA), *Photonic Crystal at FESTA in Japan - A Step Toward an Extremely Miniaturized Optical Pulse Control Device/circuit*
18:00	**Talk:** D. J. Norris, NEC Research Institute, *Self-organized 3D Photonic Crystals*
18:30	**Talk**: R. Biswas, Ames Laboratory, Iowa State University, *Structure of Colloidal Photonic Crystals*
19:00	**Talk**: H. M. van Driel, University of Toronto, *Optical Reflectivity of Strongly Photonic Crystals: Multiple Diffraction and Bragg Peaks That Do Not Move*
19:30	End of the Session

Saturday, June 24, 2000

Morning Session **Chairperson: R. Sprik**

9:00	**Lecture**: W. Vos, University of Amsterdam, *Strong Interaction between Light and Photonic Crystals Made Using Self-Assembly: II*
10:00	**Talk**: Y. Fink, Massachusetts Institute of Technology, *A Comprehensive Approach to Photonic Crystal Formation in One, Two and Three Dimensions Using Self-assembled Block Copolymer Structures*
10:30	**Talk:** J. Martorell, University of Catalunya, *Quadratic Nonlinear Interactions in Photonic Crystals*
11:00	Coffee Break
11:30	**Talk:** V. Shalaev, New Mexico State University and Univ. P. and M. Curie, *Anderson Localization of Surface Plasmons and Nonlinear Optics of Percolating Composites.*
12:00	**Talk:** J. J. Saenz, University of Madrid, *Statistical Properties of Wave transport through Surface Corrugated Waveguides*
12:30	**Talk:** D. Cassagne, University of Montpellier, *Tight-binding Wannier Function Method for Photonic Band Gap Materials*
13:00	**Talk:** B. van Tiggelen, Grenoble, *Wave Transport Around the Localization Threshold*
13:30	Lunch and Discussions

Sunday, June 25, 2000

Field Trip

Monday, June 26, 2000

Morning Session	**Chairperson: J. Page**
9:00	**Lecture**: E. Yablonovitch, University of California, Los Angeles, *Electromagnetic Band Gaps at Photonic and Radio Frequencies: I*
10:00	**Lecture**: T. F. Krauss, University of St. Andrews, *Patterned Photonic Crystal Waveguides: I*
11:00	Coffee Break
11:30	**Lecture**: A. Lagendijk, University of Amsterdam, *Localization of Light: II*
12:30	**Talk**: D. Wiersma, University of Florence, *Propagation of Light in Partially Disordered Systems*
13:00	**Talk:** P. Halevi, Puebla, Mexico, *Homogenization of 2d Periodic Composites and Photonic Crystal Optics*
13:30	Lunch and Discussions
Evening Session	**Chairperson: A. Moroz**
17:30	**Lecture**: C. Beenakker, Leiden University, *Random Matrix Theory of Random Lasers and Photonic Localization: I*
18:30	Session II: **Oral Presentation of Posters**
19:00	**Posters**
20:00	End of the Session

Tuesday, June 27, 2000

Morning Session	**Chairperson: M. Sigalas**
9:00	**Lecture**: E. Yablonovitch, University of California, Los Angeles, *Electromagnetic Band Gaps at Photonic and Radio Frequencies: II*
10:00	**Lecture**: H. Benisty, Ecole Polytechnique, Palaiseau, *Applications of 2d Photonic Crystals to Optoelectronics: I*
11:00	Coffee Break
11:30	**Talk:** A. Forchel, Wuerzburg University, *Integration of Photonic Crystals with Active Optoelectronic Devices*
12:00	**Talk**: R. B. Wehrspohn, Max-Planck Institute of Microstructure, Halle, *Electrochemically Prepared High-Aspect-ratio Pore Arrays for 2d Photonic Crystal Applications*
12:30	
13:00	Lunch and Discussions
Evening Session	**Chairperson: E. Yablonovitch**
17:30	**Lecture**: T. F. Krauss, University of St. Andrews, *Patterned Photonic Crystal Waveguides: II*
18.30	**Panel Discussion**: *Applications of Photonic Band Gap*
19:30	End of the Session

Wednesday, June 28, 2000

Morning Session	**Chairperson: H. Benisty**
9:00	**Lecture**: C. Beenakker, Leiden University, *Random Matrix Theory of Random Lasers and Photonic Localization: II*
10:00	**Talk:** Zhao-Qing Zhang, Hong Kong, *Photonic Crystals and Perturbation Theory*
10:30	**Talk:** Y. Vlasov, Ioffe Institute, *Influence of Disorder in Photonic Crystals*
11:00	Coffee Break
11:30	**Talk:** C. M. Soukoulis, Ames Laboratory, Iowa State University, *The Effects of Disorder in Photonic Band Gap Structures*
12:00	**Talk:** V. Kuzmiak, Chez Republic, *The Localization of Light in a Random 2d Dielectric Medium*
12:30	**Talk:** G. Cwilich, Yeshiva University, *Photonic Crystals and Light Localization*
12:45	**Talk:** S. Venakides Duke University, *Computational and Theoretical Results in Photonic Crystals*
13:00	**Panel Discussion**: *Photonic Band Gaps and Disorder*
13:30	Lunch and Discussions
Evening Session	**Chairperson: P. Halevi**
17:30	**Talk**: R. Biswas, Ames Laboratory, Iowa State University, *Antenna Applications of Photonic Crystals*
18:00	**Talk:** M. Sigalas, Agilent Laboratories, *Waveguide Bends in 3D Layer-by-Layer Photonic Band Gap Materials*
18:30	**Talk**: N. A. Nicorovici, University of Sydney, *Localization and Homogenization in Photonic Crystals*
19:00	**Talk:** A. Orlowski, Warsaw, *From Proximity Resonances to Anderson Localization: Universality Effects in Multiple Scattering*
19:30	End of the Session

Thursday, June 29, 2000

Morning Session — Chairperson: T. F. Krauss

9:00	**Lecture**: H. Benisty, Ecole Polytechnique, Palaiseau, *Applications of 2d Photonic Crystals to Optoelectronics: II*
10:00	**Talk:** D. Chigrin, University of Wuppertal, *One-Dimensional Photonic Crystals: Omnidirectional Reflection and Superprism Phenomena*
10:30	**Talk:** A. Moroz, Ultrech University, *Complete Photonic Band Gap Structures Below Infrared Wavelengths*
11:00	Coffee Break
11:30	**Lecture**: E. Yablonovitch, University of California, Los Angeles, *Electromagnetic Band Gaps at Photonic and Radio Frequencies: III*
12:30	**Panel Discussion**: *Photonic Crystals and Optoelctronic Devices*
13:30	Lunch and Discussions

Evening Session — Chairperson: C. M. Soukoulis

17:30	**Remarks and Discussion**: *Open and Future Directions*
18:00	**Panel Discussion**: *Open and Future Directions*
19:30	**Closing Session**: End of the Institute

Abstracts of Lectures and Talks

Monday, June 19, 2000

8:30	Registration
9:30	Opening and Welcoming Remarks

Morning Session Chairperson: E. N. Economou

10:00 **Lecture**: J. D. Joannopoulos, Massachusetts Institute of Technology, *The Magical World of Photonic Crystals: I*

Within the past several years we have witnessed the emergence of a new class of materials which provide capabilities along a new dimension in the control and manipulation of light. These materials, known as "photonic crystals," are viewed ideally as a composite of a periodic array of macroscopic dielectric scatterers in a homogeneous dielectric matrix. A photonic crystal affects the properties of a photon in much the same way that a semiconductor affects the properties of an electron. Consequently, photons in photonic crystals can have band structures, localized defect modes, surface modes, etc. This new ability to mold and guide light leads naturally to many novel applications of these materials as optoelectronic components. An introductory survey including recent exciting developments in the field of photonic crystals is presented.

11:30 **Lecture**: A. Lagendijk, University of Amsterdam, *Localization of Light: I*

We will introduce and review the concept of localization of light. Ideas will be illustrated using some new experimental results. Experiments that will be discussed are transmission and enhanced backscattering. We will show that a recently introduced interferometric technique allows us to obtain phase information as well as to perform measurements with very short time scales.

12:30 **Lecture**: J. Pendry, Imperial College, *Computing the Response of Structured Metals to Light*

Metals present special challenges to computation and the problems are directly related to the plasmon modes they support. In a dielectric insulator details of the electromagnetic fields are confined to the scale of the wavelength of light in the dielectric. This limit is very helpful when planning a computation particularly if we use a real space description of the fields. Insulators are easy targets for computation in another respect: their dielectric functions tend to be independent of frequency and therefore we are free to use a variety of techniques including time domain methods.

Metals belong to the awkward squad when it come to calculation. The length scale of the wavefield can vary from the wavelength of light in free space down to the smallest detail of the metallic structure. Extreme concentrations of radiation into a few cubic nanometres are not uncommon and must be described in detail if an accurate overall response is to be calculated.

To handle these difficulties the transfer matrix method is commonly used as it computes at a fixed frequency. Hence dispersion of the dielectric function is not a problem. Another technique that is employed for metals is the adaptive mesh whereby the grid of points on which the field is specified expands or contracts according to the details expected in the fields. As it happens there are particularly easy ways of implementing this potentially tricky technique without rewriting computer code. Finally it is possible to adapt the 'FDTD', finite difference time domain, methods to work for dispersive materials whilst retaining the advantageous 'order N' scaling of this methods with system size.

Evening Session Chairperson: S. John

17:30 **Lecture**: S. Lin, Sandia National Laboratory, *Microfabrication of 2d and 3d Photonic Crystals: I*

In this talk, the challenges and promises of three-dimensional (3D) photonic crystals in the infrared and optical wavelengths will be described. Emphasis will be placed on historical development, nano-fabrication techniques, construction of high-Q cavities, and the alternation of emission process by 3D photonic crystals. Additionally, the realization of a new class of 2D photonic crystal slab structures will be reported. The 2D crystal is capable of fully confining light and operates at 1.5mm communication wavelengths.

18:30 **Panel Discussion**: *Photonic Band Gaps*

19:30 End of Session

Tuesday, June 20, 2000

Morning Session Chairperson: A. Lagendijk

9:00 **Lecture**: J. D. Joannopoulos, Massachusetts Institute of Technology, *The Magical World of Photonic Crystals: II*

10:00 **Lecture**: S. John, Toronto, *A Theoretical Roadmap for 3-d Photonic Band Gap Materials and Their Uses: I*

Unlike semiconductors which facilitate the coherent propagation of electrons, photonic band gap (PBG) materials execute their novel functions through the coherent localization of photons. I review and discuss our recent synthesis of a large scale three-dimensional silicon photonic crystal with a complete photonic band gap near 1.5 microns. When a PBG material is doped with impurity atoms which have an electronic transition that lies within the gap, spontaneous emission of light from the atom is inhibited. Inside the gap, the photon forms a bound state to the atom. Outside the gap, radiative dynamics in the colored vacuum is highly non-Markovian. I discuss the influence of these memory effects on laser action. When spontaneous emission is absent, the next order radiative effect (resonance dipole-dipole interaction between atoms) must be incorporated, leading to anomalous nonlinear optical effects which occur at a much lower threshold than in ordinary vacuum. I describe the collective switching of two-level atoms near a photonic band edge, by external laser field, from a passive state to one exhibiting population inversion. This effect is forbidden in ordinary vacuum. Finally, I discuss the prospects for a phase sensitive, single (3-level) atom quantum memory device, onto which information may be written by an external laser pulse.

11:30 **Lecture**: E. Ozbay, Bilkent University, *Physics and Applications of Photonic Crystals*

Photonic crystals are three dimensional periodic structures having the property of reflecting the electromagnetic (EM) waves in all dimensions, for a certain range of frequencies. Defects or cavities around the same geometry can also be built by means of adding or removing material. The electrical fields in such cavities are usually enhanced, and by placing active devices in such cavities, one can make the device benefit from the wavelength selectivity and the large enhancement of the resonant EM field within the cavity. We used three-dimensional photonic crystals to demonstrate resonant cavity enhanced detectors and antennas, and waveguiding.

We have demonstrated the resonant cavity enhanced (RCE) effect by placing microwave detectors in defect structures built around dielectric and metallic based photonic crystals. A power enhancement factor of 3450 was measured for planar cavity structures built around dielectric based photonic crystals. A resonant antenna was also built around the same structure. We measured a maximum directivity of 310, and a power enhancement of 180 at the resonant frequency of the cavity. The measured radiation patterns agree well with our theoretical results.

We used the defect structures to demonstrate waveguiding around layer-by-layer photonic crystals. An air gap introduced between two photonic crystal walls was used as the waveguide. We observed full (100%) transmission of the electromagnetic (EM) waves through these planar waveguide structures within the frequency range of the photonic band gap. The dispersion relations obtained from the experiment were in good agreement with the predictions of our waveguide model. By using coupled periodic defects, we have also experimentally observed a new type of waveguiding in a photonic crystal. A complete transmission was achieved throughout the entire waveguiding band.

12:30 **Lecture**: S. Noda, Kyoto, *Semiconductor Photonic Crystals*

In this talk, I would like to review the present status of 3D and 2D photonic crystals based on III-V semiconductors. On the 3D photonic crystals, the development of complete photonic crystals in optical wavelengths, and their applications to 3D sharp bend waveguide and control of light-emission will be discussed. On the 2D photonic crystals, a very unique coherent oscillation of 2D photonic crystal laser and some other functional devices will be described.

Evening Session Chairperson: Kurt Busch

17:30 Session I: **Oral Presentation of the Posters**

18:00 - 19:30 **Posters**

Wednesday, June 21, 2000

Morning Session Chairperson: J. D. Joannopoulos

9:00 **Lecture**: J. Pendry, Imperial College, *Intense Focusing of Light Using Metals*

We are familiar with the fact that in vacuum light may only be focused to an area of the same order as the wavelength. However metal surfaces support plasma modes that couple to incident light, and the focusing of surface plasma modes is not restricted by the free space wavelength. Such nanofocusing offers the possibility of huge concentrations of radiative energy in very small volumes, impossible to achieve with conventional focusing with lenses. For very modest power input, local concentrations of energy may be great enough to excite nonlinear effects that depend on the intensity.

In fact most nanostructured metal surfaces will produce such focusing as evidenced by the Surface Enhanced Raman effect which is known to be due to intense local concentrations of electric field. Further evidence of intense local field concentrations is dramatically demonstrated in recent experiments by Ebbesen et al., who studied transmission of light at a wavelength of 1500 nanometres, through a 200-nanometre-thick silver film into which cylindrical holes with a diameter of 150 nanometres had been cut. In this system light plays this Houdini-like trick by coupling to surface modes of the metal that are very closely confined to the surface and therefore find it much easier to filter through the tiny holes, as demonstrated in a recent theoretical paper.

10:00 **Lecture**: S. John, Toronto, *A Theoretical Roadmap for 3-D Photonic Band Gap Materials and Their Uses: II*

11:30 **Lecture**: E. N. Economou, Research Center of Crete, *Acoustic waves in Ordered and Disordered Systems: Recent Advances: I*

A brief review of the equations governing wave propagation in composite fluid-fluid, fluid-solid and solid-solid ordered and disordered systems will be presented together with relevant experimental and theoretical results. The role of multiscattering will be emphasized and demonstrated by considering acoustic propagation in bubbly water. Finally, preliminary recent results in exciting by light scattering optical-like vibrational modes in solutions containing copolymers will be presented.

12:30 **Talk**: C. T. Chan, Hong Kong, *Photonic Crystals From Metal-coated Spheres*

We show theoretically and experimentally that photonic band gaps can be realized using metal or metal-coated spheres as building blocks. Robust photonic gaps exist in any periodic structure built from such spheres when the filling ratio of the spheres exceeds a threshold. The frequency and the size of the photonic gap are essentially determined by the local order and they are not sensitive to the symmetry or the global long range order. These photonic crystals can withstand a large amount of disorder. For example, stacking faults cause almost no degradation. The gaps persist even in a random packing of such spheres. Good agreement between theory and experiment is obtained in the microwave regime. Calculations show that the approach can be scaled up to IR and optical frequencies.

Work done in collaboration with Z.L. Wang, W.Y. Zhang, X.Y. Lei, D.G. Zheng, W.Y. Tam and P. Sheng

Evening Session Chairperson: D. A. Papaconstantopoulos

17:30 **Lecture:** E. N. Economou, Research Center of Crete, *Acoustic Waves in Ordered and Disordered systems: Recent Advances: II*

18:00 **Talk:** J. Page, University of Manitoba, *Acoustic Band Gap Materials*

We use ultrasonic experiments to study the acoustic analogue of photonic crystals. As an illustrative example, we present recent pulsed transmission measurements on hexagonal close packed (hcp) arrays of 0.80-mm-diameter stainless steel beads immersed in water. High quality crystals are prepared, starting with extremely monodisperse steel beads, by using a manual assembly technique. We directly measure the ultrasonic wave field transmitted through slab-shaped samples of different thicknesses, allowing us to determine both the dispersion curve and amplitude transmission coefficient. We compare our experimental results with theoretical calculations based on multiple scattering theory (MST) for elastic waves, which is ideally suited to the spherical scatterer geometry of the present experiments. We find that the low-frequency band structure and transmission coefficient calculated using this approach are in very good agreement with our experiments.

Work performed in collaboration with A.L. Goertzen, Zhengyou Liu, C.T. Chan and Ping Sheng

18:30 **Talk:** F. J. Garcia-Vidal, University of Madrid, *Surface Plasmons of Lamella Metallic Gratings*

Surface electromagnetic modes (surface plasmons) of lamellar metallic gratings with very narrow and deep grooves or slits are reviewed from the theoretical point of view. In the reflection configuration [1] we will show how there are basically two kind of modes: surface plasmon polaritons (SPPs) and waveguide resonances in which light is strongly localized inside the grooves. Experimental evidence of the excitation of these two kind of plasmons in the optical regime is also given. In the transmission configuration [2], transmission resonances associated to the excitation of surface plasmons of the grating can appear in the spectrum. We will show that there are two possible ways of transferring light from the upper surface to the lower one: by the excitation of coupled SPPs on both surfaces or by the coupling of the incident light with waveguide resonances located in the slits. Both mechanisms can lead to almost perfect transmittance for those particular wavelengths.

19:00 **Talk:** D. R. Smith, University of California, San Diego, *Left-handed Materials*

We have recently introduced a new periodic metallic structure1 based on two interlaced lattices of straight wires2 and Split Ring Resonators3. The size of the scattering elements and the lattice constant are significantly less than the incident wavelength (at frequencies of interest), so that the system can be considered as an effective medium characterized by frequency-dependent material constants. By simulations and experimental measurements, we demonstrate a frequency band where both material constants-the permittivity (e) and permeability (m)-are simultaneously negative. When both material constants are negative, Maxwell's Equations allow for plane wave solutions, but with a twist: ExB is in the direction of -k rather than +k for plane waves, and thus a "left-hand" rule relates the three vectors. The result of this simple reversal is that many common electromagnetic phenomena, such as the Doppler shift, Cerenkov radiation, and even Snell's Law, are also reversed4, leading to the potential of novel electromagnetically active materials and surface coatings based on LH media.

Thursday, June 22, 2000

Morning Session Chairperson: J. Pendry

9:00 **Lecture**: Ad Lagendijk, University of Amsterdam, *Random Lasers*

Disordered systems that can both scatter and amplify light have emerged as an exciting field. We will discuss in some detail the threshold behaviour while presenting some new experimental and theoretical results.

All our papers are availabale on line. This collection includes review papers, tutorials, and a collection of hight-quality Dutch theses on multiple scattering, localization, and random lasers:

10:00 **Talk:** H. Cao, Northwestern University, *Localization of Laser Light in Active Random Media*

We have observed random laser action in highly disordered semiconductor powder and polycrystalline films. Since the scattering mean free path is less than the emission wavelength, recurrent light scattering arises and provides coherent feedback for lasing. Above the lasing threshold, discrete lasing modes appear in the spectrum in addition to a drastic increase of emission intensity. Our measurement of spatial distribution of laser light intensity indicates that photons are localized in spatial regions of the size on the order of optical wavelength. The laser emission from the random media can be observed in all directions. In addition to macroscopic-scale random media, we have observed lasing action in micrometer-sized random media. This discovery leads to the fabrication of microlaser with disordered medium. Anderson localization of light provides a new physical mechanism of optical confinement for microlaser.

11:30 **Talk**: Z. Vardeny, University of Utah, *Random and Distributed Feedback Lasing in Opal Photonic Crystals*

Stimulated emission and lasing have been studied in various scattering gain media, including luminescent B-conjugated polymer films and opal micro-crystals infiltrated with polymer or dye solutions. In addition to amplified spontaneous emission that is usually observed in high gain media upon intense photoexcitation, a lasing process was revealed using stripe excitation geometry. The new emission regime is characterized by a finely structured spectrum with narrow lines, of the order of 0.1nm. We interpret this laser like emission as due to random lasing where the optical feedback is provided by weak light scattering inside the gain medium. Coherent back-scattering measurements of the same media systems were found to be in agreement with this interpretation.

In addition we demonstrate a three-dimensional photonic crystal laser based on infiltrated dyes in a single crystal opal, operating simultaneously in the blue (435nm) and red (670-720nm) spectral regions. The feedback mechanism underlying this type of laser is the Bragg scattering off different sets of crystalline (hkl) silica planes, via a distributed feedback process. The laser emission wavelength was selected by proper orientation of the lasing axis with respect to the [111] and [220] directions for the red and blue lasing, respectively. Defect modes caused by stacking faults in the opal crystal were identified in the laser spectrum as sharp lines, which were found to depend on the specific illuminated area on the opal surface.

12:00 **Lecture**: C. M. Soukoulis, Ames Laboratory, Iowa State University, *Theory and Simulation of Random Lasers*

Disordered systems that both scatter and amplify light (the so-called random lasers) have been a fascinating subject to study. Over the last five years, there have been substantial theoretical and experimental efforts to unravel the mechanism that gives rise to this amazing behavior.

A model to simulate the phenomenon of random lasing is presented. It couples Maxwell's equations with the rate equations of electronic population in a disordered system. Finite difference time domain methods are used to obtain the field pattern and the spectra of localized lasing modes inside the system. A critical pumping rate exists for the appearance of the lasing peaks. The dependence of on the length of the system and the strength of disorders is obtained. The number of lasing modes increases with the pumping rate and the length of the system. There is a lasing mode repulsion. This property leads to a saturation of the number of modes for a given size system and a relation between the localization length and average mode length . Similar behavior is expected to be seen in photonic crystals, too.

13:00 **Talk:** J. P. Woerdman, Leiden University, *Special Resonators for Random and Fractal Lasers*

Random lasers do not necessarily require strong microscopic scattering. A suitably designed multi-mode laser cavity can act as a nonresonant system if it supports a manifold of spectrally overlapping modes. This manifold must have equal mode losses and strong mixing. We will discuss various cavity configurations within this category. Particularly interesting is the geometrically-unstable cavity, which has chaotic ray characteristics. The mode patterns of this cavity are self-similar and are characterized by a fractal dimension (Nature 402, 138 (1999).

Evening Session Chairperson: K. Asakawa

17:30 **Talk:** S. Lin, Sandia National Laboratory, *Microfabrication of 2d and 3d Photonic Crystals: II*

18:00 **Talk:** T. Baba, Yokohama National University, *Light Propagation Characteristics in Defect Waveguides in a Photonic Crystal Slab*

Channel waveguides composed of a series of defects in an air hole photonic crystal slab was characterized theoretically and experimentally. They were similar to GaInAsP/SiO2/InP waveguides described in the first reports [1,2]. We employed the SOI wafer for stable fabrication of long guides. The light transmission through the waveguides was confirmed in > 100-um-long waveguides at wavelengths of 1.47 to 1.60 um. The propagation loss was measured by the Fabry-Perot resonance method to be less than 3 dB for a waveguide length of 56 um. The dependence of the propagation loss on wavelength, slab thickness, channel width, etc., will be discussed with 3-D FDTD simulations. The possibility of various lightwave devices[3], i.e. sharp bends, Y blanches and directional couplers will also be discussed.

18:30 **Talk**: D. C. Allan, Corning Incorporated, *Photonic Band Gap Fibers for Real World Applications*

Conventional telecommunication optical waveguide glass fiber is the backbone of the internet revolution. This highly optimized and highly transparent material consists of a higher index core glass inside a lower index clad glass. Light is localized in the core by total internal reflection at the core/clad boundary. The transmission range between amplifiers of today's fibers, about 70km, is limited in part by the small but nonzero optical nonlinearity of silica. It is also limited in part by the small but nonzero amount of intrinsic scattering. It has recently been demonstrated, both theoretically[1] and experimentally[2], that photonic band gap confinement can be used to form a new kind of optical waveguide fiber. This photonic band gap fiber (PBGF) guides light in a LOW index core, in contrast to conventional fiber waveguides. This low index core can be air, allowing for dramatic reduction in nonlinearity and scattering. This presentation describes the fabrication of photonic band gap fibers, their experimental characterization, their predicted properties, and their significance in the context of optical telecommunication.

19:00 **Talk:** R. E. Slusher, Lucent Technology—Bell Laboratories, *Symmetry, Laser Action, and Output Couling in 2d Photonic Crystals*

We have investigated the lasing and output coupling characteristics of two-dimensional photonic crystals. The lasers/couplers are experimentally realized with organic semiconductors and involve photo-excitation of patterned combinations of organic semiconductor and dielectrics (e.g., SiO_2). The patterning is accomplished by advanced optical lithography or electron-beam lithography followed by dry etching and the subsequent deposition of the organic gain medium as a thin coating. We show that by employing advanced optical lithography, which is driven by silicon electronics, feature sizes required for photonic crystals that operate in the visible can be attained. Organic media are also very convenient in investigating the basic physics of novel resonators and optical structures [1]. Most of the photonic crystals employed in this work do not possess a complete gap; however theoretical extensions of this work to systems with a complete bandgap will be discussed along with some experimental data.

The basic principle employed in our designs is based on our recent discovery that the output coupling characteristics of two-dimensional gratings (or PC's) are significantly different from one-dimensional gratings. Since we do not employ the lowest energy bandstructure features to provide the feedback necessary for laser oscillation, phase matching conditions result in diffractive coupling of some of the laser emission out of the plane of the waveguide. In two-dimensional PC's, phase matching conditions result in the coupling of light to one or a discrete number of directions instead of a cylindrical wave. We have designed numerous combinations of lasers and couplers which have the potential to couple to a single spot normal to the plane of the waveguide.

One design that has been successfully implemented is a square two-dimensional PC, which functions as a laser and output coupler. Detailed theoretical calculation show that a careful study of band-structure features is required to attain an accurate understanding of mechanism of laser action in two-dimensional photonic crystals. Laser action occurs at points in the Brillouin zone where the density of photon states is peaked and where the photon group velocity goes to zero. Laser action does not necessarily take place at band extrema; occurring at saddle points were the density of states is sometimes higher. We have also found a variety of ways to combine lasers and couplers resulting in composite devices with interesting and potentially useful optical properties.

Friday, June 23, 2000

Morning Session Chairperson: D. J. Norris

9:00 **Lecture**: W. Vos, University of Amsterdam, *Strong Interaction Between Light and Photonic Crystals Made Using Self-Assembly: I*

The following issues will likely be discussed: - the fabrication of 3D photonic crystals that strongly interact with light and that are made using self-organizing systems as templates, and new developments. - the detailed characterization of the crystals, by electron microscopy and by synchrotron small-angle x-ray scattering. - optical experiments such as reflectivity, transmission, enhanced backscattering, phase-sensitive ultrashort-pulse interferometry. - studies of the emission by light sources (excited molecules or atoms) located *inside* photonic crystals, both cw and time-resolved. - the interpretation of the experiments.

10:00 **Lecture**: K. Busch, University of Karlsruhe, *Tunable Photonic Crystals*

We demonstrate that complete three-dimensional Photonic Band Gaps (PBG), spanning roughly 10% and 15% of the gap center frequency are attainable by incomplete infiltration of an opal with silicon and germanium, respectively. In addition, we show that when an optically birefringent nematic liquid crystal is infiltrated into the void regions of an inverse opal PBG material, the resulting composite material exhibits a completely tunable PBG. Measurements on analogous two-dimensional Photonic Crystals show that the photonic band edge may be shifted by more than 100 nm. Furthermore, we present results of bandstructure calculations for Photonic Crystals whose constituent materials exhibit Faraday or natural optical activity. This provides additional flexibility for tuning the optical properties of Photonic Crystals.

11:30 **Talk**: F. Meseguer, University of Valencia, *Inverse Opals Fabrication*

Here we report on different approaches to the fabrication of inverse opals. We start from silica opal templates with sphere size in the range between 200 nm and 1300 nm. The opal porous lattice is fully (above 90 % of the opal void volume) infiltrated with semiconductors (CdS, Ge) as well as polymers by several methods. Afterwards, the template is removed, from the composite, by a soft chemical etching method. Thus, and inverse opal is obtained. The periodicity of the template can be chosen to guarantee that photonic gaps or pseudogaps are in the transparency region of the bulk infiltrated material.

Optical properties of CdS, Ge, and polymer inverse opals, as well as the comparison with a theoretical calculations of the transmission and reflectance are reported. Ge inverse opal has a huge refractive index contrast (4) well above the onset value to present a sizeable full band gap.

12:00 **Talk**: A. van Blaaderen, Ultrech University, *Manipulating Colloidal Crystallization for Photonic Applications*

Colloidal particles are the ideal building blocks for photonic crystals because their properties can be tuned by chemical modification and their self-organization or crystallization into 3D periodic lattices can be manipulated by changing the interaction potentials between the particles and by using external fields. In this contribution we focus 1) on how large colloidal crystals with known crystal orientation and symmetry can be grown by colloidal epitaxy. And 2) how colloidal crystallization can be manipulated by electric fields; both in symmetry, size and orientation of the crystals.

12:30 **Talk**: S. G. Romanov, University of Wuppertal, *Light Manipulation of 3d Templated Photonic Crystals*

The photonic energy band structure, resulting from a suitable periodic modulation of dielectric properties in a solid, makes it possible to control the propagation and emission of light without dissipation. To realise the full extent of these possibilities, electromagnetic waves have to be confined in 3-dimensions. Three-dimensional crystalline packages of silica or polymeric balls (synthetic opals and similar structures) as well as their replicas, i.e. inverted opal, have been recognised as suitable models of 3-dimensional photonic crystals. In our lecture the following topics related to experimental studies of templated opal-based photonic crystals operating in the visible range of spectrum will be discussed: Technological aspects of the fabrication of 3D opal-like and opal-templated photonic crystals. Examination techniques and results. Bragg diffraction from silica- and polymeric-based photonic crystals, mapping of corresponding anisotropic photonic bandgap structures. Enhancement of the photonic stop-band (bandgapwidth enlargement, bandgap dispersion smoothening) by means of infilling and coating opals with high refractive index materials (S, TiO2, CdS, InP, GaP) and inversion of opals. Comparison of stop-band characteristics of bulk and thin-film opal-like photonic crystals Design and testing of organic-inorganic opal-based photonic crystals (e.g. opal-TiO2-polymer-dye/rare earth ion structures). Peculiarities of light propagation in photonic crystals with double PBG structure (GaP-opal/Air-opal). Probing the density of photonic states in opal-like photonic crystals. Self-focusing of the emission from opal-like photonic crystals, focusing enhancement with the increase of the refractive index contrast. Modelling of this effect using the superprism approach.Probing the changes in the spontaneous emission rate of emitters embedded in photonic crystals. Comparison of emission from wide (laser dyes) and narrow (rare earth ions) band emitters embedded in photonic crystals. Prospective opal-based device structures.

13:00 **Talk:** A.Polman, FOM, Amsterdam, *Fabrication and Characterization of Silicon-based Photonic Band Gap Materials*

Silicon is one of the best known materials in the world. It is available in high purity and the processing technologies for silicon are by now very well established. While the properties of silicon as a semiconductor are well explored, it is not much used in photonic technology. However, Si is an excellent optical waveguide material, as it is completely transparent at 1.5 μm. In this work we have exploited silicon as a substrate and optical waveguide material in a variety of novel photonic structures. Our experiments focussed on a) the design of two-dimensional photonic bandgap structures, b) measurements on the spontaneous emission rate of atoms to probe the local optical density of states. 2-D photonic crystal waveguides are fabricated in Si by reactive ion etching of Si pillars that are 5 mm tall, 205 nm in diameter, and arranged in a square lattice with a 570 nm pitch. Bandstructure calculations predict a gap for TM modes at a wavelength of 1.5 mm with a gap width equal to 37 % of the center energy. In order to meet the severe nano-tolerance requirements in such a device, the SF6/O2 electron cyclotron resonance plasma process conditions at reduced temperature are optimized. By removing an array of Si pillars, the waveguide is defined. In order to achieve confinement in the third dimension, a 2 μm thick region of the Si structure was amorphized before processing, using 4 MeV Xe irradiation. Input and output waveguides are integrated with the structure. In order the measure the local density of states in such photonic structures, optical probe ions must be incorporated. We have studied Er ion implantation into Si and found the optimum implantation and annealing conditions to obtain optically active Er, luminescing at 1.535 μm in Si. The luminescence shows strong quenching above 200 K, but lifetimes as long as 1 ms are achieved at 77 K. We have also studied the coating of the Si pillar structures with a novel wet chemical process, in which we have used a reaction between tetraethoxysilane, ammonia, and water to nucleate and grow well-controlled layers of SiO2 on surfaces with extreme aspect ratio. Using confocal microscopy we show the uniform coating of such layers doped with an eosin dye. Finally, we show how we can strongly affect the radiative lifetime of Er probe ions implanted into silica colloidal particles with a diameter of 300 nm, by comparing three geometries, 1) placed on a Si substrate, 2) arranged in a 3-D crystal, or 3) surrounded by an index-matching fluid.

Evening Session Chairperson: A. Polman

17:30 **Talk**: K. Asakawa, The Femtosecond Technology Research Association (FESTA), *Photonic Crystal at FESTA in Japan - A Step Toward an Extremely Miniaturized Optical Pulse Control Device/Circuit*

AlGaAs-based two-dimensional photonic band-gap crystal (PBC) slab test devices have been fabricated using electron beam lithography and a reactive ion beam etching technology. Air hole-based triangular lattices with lattice constants ranging from 0.32 to 0.45 have been fabricated on both semiconductor-clad (SC) and air-bridge (AB) structures. In a transmission/reflection spectrum with wavelength ranging from 0.85 to 1.1 mm on an SC-type device, a band-gap with large attenuation more than 30 dB has been observed for both E- and H-polarization. Quantitatively more precise characteristics are now under measurement using a sub-ps pulse propagation technique. Prospect for achievement of a PBC-based optical pulse control device involving a branching/interferometer waveguide with optically nonlinear (NL) medium will be addressed. A site-controlled quantum dot assisted with a nano-probe technique will also be shown as a representative of NL medium. An AB-type device will be presented at a poster session in the meeting. This work was supported by NEDO within the framework of the Femtosecond Technology Project.

18:00 **Talk:** D. J. Norris, NEC Research Institute, *Self-organized 3D Photonic Crystals*

Recently colloidal self-organization has been used to make 3D photonic crystals from a variety of materials. A typical approach is to induce sub-micron silica spheres to organize on an fcc lattice. This template, which is periodic on an optical length scale, then serves as a three-dimensional scaffolding into which another material may be infiltrated. Subsequent removal of the template by selective etching then yields a 3D photonic crystal, also called an inverted opal. These structures are particularly interesting since they have been predicted to exhibit an omnidirectional photonic band gap and enhanced optical nonlinearities. Here we show how to use colloidal self-organization to make three different materials: 1) semiconductors to explore high refractive index contrast, 2) metallo-dielectrics to explore coupling to plasmons, and 3) conjugated polymers to explore optical nonlinearities. We then discuss the optical properties of our photonic crystals. In particular, we use optical microscopy to probe a single crystalline domain in each of our samples. By measuring spatially resolved reflection and emission spectra, inhomogeneities due to averaging over inherent disorder (always present in self-assembled photonic crystals) can be eliminated. "Defect-free" spectra are obtained, from which the intrinsic photonic band structure can be extracted. Furthermore, this technique allows us to probe the specific band structure at higher frerquencies, up to the "4th-order" stop band. This capability is important since the omnidirectional photonic band gap should at the "2nd-order" stop band in inverted opals (i.e. between the 8th and 9th bands).

18:30 **Talk**: R. Biswas, Ames Laboratory, Iowa State University, *Structure of Colloidal Photonic Crystals*

I will survey theoretical calculations and experimental measurements on colloidal photonic crystals synthesized at iowa State university. These crystals show reflectivity peaks at optical wavelengths. Optical mesurements on these photonic crystals indicate a geometry that is considerably distorted from ideal. band structure calculations of the positions of the stop bands will be utilized to determine the structure of the crystal and refractive index of the background material. the dependence of photonic properties with stacking and disorder will also be discussed. Alternative photonic lattices with photonic gaps will be discussed. (In collaboration with G. Subramania, K. Constant, M. M. Sigalas, K.-M. Ho, C. M. Soukoulis.) Supported by the U.S. Dept. of Energy/Office of basic Energy Sciences.

19:00 **Talk**: H. M. van Driel, University of Toronto, *Optical Reflectivity of Strongly Photonic Crystals: Multiple Diffraction and Bragg Peaks That Do Not Move*

We report results of angle, polarization and frequency resolved optical reflectivity measurements on fcc crystals consisting of air spheres in titania. The carefully grown crystals show excellent structural order, as confirmed by x-ray scattering and electron microscopy. The reflectivity spectra of these strongly photonic crystals show unusual features in comparison to simple Bragg diffraction of weakly photonic crystals. Over a wide range of reflection angles, the (111) Bragg peak splits into at least two peaks that show an avoided crossing. Calculated photon dispersion curves show that the multiple peaks result from band repulsions of Bloch states due to simultaneous (200) and (111) Bragg resonances . Such multiple Bragg diffraction results in flat dispersion relations, and thus plays an essential role in photonic band gap formation. In the range of the 2nd order Bragg diffraction, where a complete photonic band gap is predicted for fcc crystals with higher dielectric contrast than our materials, at least three peaks are observed with central frequencies independent of reflection angle over a wide range. Theoretical analysis allows us to assign these peaks to stop-gaps or characteristics of dispersionless bands. A significant conclusion is that reflectivity spectra can mimic the signature of a complete photonic band-gap without such a band-gap actually being present . We thank Judith Wijnhoven for sample preparation, Henry Schriemer and Rudolf Sprik for discussions, and Ad Lagendijk especially for organizing HMvD's visit.

Saturday, June 24, 2000

Morning Session Chairperson: R. Sprik

9:00 **Lecture**: W. Vos, University of Amsterdam, *Strong Interaction between Light and Photonic Crystals Made Using Self-Assembly: II*

10:00 **Talk**: Y. Fink, Massachusetts Institute of Technology, *A Comprehensive Approach to Photonic Crystal Formation in One, Two and Three Dimensions Using Self-assembled Block Copolymer Structures*

A conceptual framework for creating photonic crystals from self-assembling block copolymers has been formulated. In order to form useful band gaps in the visible regime, periodic dielectric structures made of typical block copolymers need to be modified to obtain appropriate characteristic distances and dielectric constants. moreover, the absorption and defect concentration must also be controlled. This affords the opportunity to tap into the large structural repertoire, the flexibility and intrinsic tunability that these self-assembled block copolymer systems offer. A symmetric poly(styrene-b-isoprene) (~400k M) block copolymer was used to achieve a photonic band gap in the visible regime. By swelling the diblock copolymer with lower molecular weight constituents, we have been able to control the location of the sotp band across the visible regime. one and three-dimensional crystals have been formed by changing the volume fraction of the swelling media. Methods for incorporating defects of prescribed dimensions into the self-assembled structures have been explored leading to the construction of a microcavity light-emiting device.

10:30 **Talk:** J. Martorell, University of Catalunya, *Quadratic Nonlinear Interactions in Photonic Crystals*

Soon after the birth of the field of photonic crystals it became clear that the intrinsic properties of such materials made them very suitable to control the nonlinear interaction between the radiation and matter. In this presentation, I will show that some of these properties are particularly useful when the interaction that we consider is the second order nonlinear interaction. For an efficient generation of second harmonic light or for any other type of efficient parametric interaction, one must combine, within the same material, a lack of inversion symmetry and a large nonlinearity with a phase matching mechanism. I will present experimental evidence that 3-dimensional photonic crystals offer the ideal frame to combine in the same material these three requirements. On the other hand, I will show that 1-dimensionl truncated periodic structures can be used to enhance cascaded second order nonlinear interactions and at the same time eliminate the phase sensitivity of this type of quadratic interaction.

11:30 **Talk:** V. Shalaev, New Mexico State University and Univ. P. and M. Curie, *Anderson Localization of Surface Plasmons and Nonlinear Optics of Percolating Composites.*

Anderson localization of surface plasmons in random metal-dielectric composites near the percolation threshold has been predicted and observed using scanning near-field optical microscopy. A scaling theory of local-field distributions and optical nonlinearities is developed. The theory predicts that the local fields are very inhomogeneous and consist of sharp peaks representing localized surface plasmons (sp). The localization maps the Anderson localization problem described by the random Hamiltonian with both on- and off-diagonal disorder. The local fields exceed the applied field by several orders of magnitudes resulting in giant enhancements of various optical phenomena. The white-light generation dramatically enhanced by the localized sp has been experimentally obtained. A feasibility of nonlinear single-molecule spectroscopy in percolation films has been shown.

12:00 **Talk:** J. J. Saenz, University of Madrid, *Statistical Properties of Wave transport through Surface Corrugated Waveguides*

Statistical properties of waves transmitted [1] and reflected [2] from random media are discussed in terms of Random Matrix Theory (RMT). Exact numerical calculations in surface randomly corrugated waveguides are presented. By increasing the length of the disordered region, we are able to analyze the transition from ballistic to diffusive regimes as well as from diffusion to localization in detail. Although the transport in these systems is strongly nonisotropic, the analysis of the probability distributions of both the transport coefficients and the spatial intensity [3] remarkably agrees with the analytical predictions of RMT. Our results predict unexpected strong finite size effects when the number of propagating channels is small [3].

12:30 **Talk:** D. Cassagne, University of Montpellier, *Tight-binding Wannier Function Method for Photonic Band Gap Materials*

Using the concept of generalized Wannier functions, adapted form the electronic theory of solids, we demonstrate for two-dimensional photonic crystals the existence of a localized state basis and we establish an efficient computational method allowing a tight-binding-like parameter free modelization of any dielectric structure deviating from periodicity. Examples of numerical simulations using this formalism, including modal analysis of microcavities and waveguides and calculaitons of the transmission coeffcicients are presented to prove the ability of this approach to dela accurately with large scale systems and complex structures.

13:00 **Talk:** B. van Tiggelen, Grenoble, *Wave Transport Around the Localization Threshold*

I present a new theory that is capable of describing coherent backscattering and transmission of waves very close to the mobility edge of localization. Theory is a generalization of the self-consistent theory of localization, devised 20 years ago by Götze, Vollhardt and Wölfle. It is able to deal with boundary condition, an important requirement for a quantitative describtion of coherent backscattering. A comparison will be presented to experiments conducted in Florence and Amsterdam.

Monday, June 26, 2000

Morning Session Chairperson: J. Page

9:00 **Lecture**: E. Yablonovitch, University of California, Los Angeles, *Electromagnetic Band Gaps at Photonic and Radio Frequencies: I*

Engineering design is sometimes inspired by Nature. The natural world is filled with crystals, periodic structures that interact with Schrodinger Waves. Drawing on this analogy, we are designing artificial crystal structures which are intended for Electromagnetic Waves instead. This has now unleashed the collective scientific imagination, engendering a profusion of synthetic electromagnetic crystal structures. In correspondence to semiconductor crystals these usually have an electromagnetic bandgap, a band of frequencies in which electromagnetic waves are forbidden. We will present a pictorial portfolio of various 2 and 3 dimensional crystal structures which have been conceived, and indicate the applications, such as opto-electronic light emitters, radio antennas, and color pigments, for which they are intended. In addition we will emphasize some of the new ideas that will be important for the future, including the further development of radio frequency bandgap structures, and of surface plasmon band structure.

10:00 **Lecture**: T. F. Krauss, University of St. Andrews, *Patterned Photonic Crystal Waveguides: I*

I will review the development of semiconductor-based planar photonic crystals, highlight the underlying concepts, materials and fabrication issues and point towards important issues for device applications. Examples of successful photonic crystal-based devices include photonic crystal waveguides and photonic integrated circuit elements as well as lasers and LEDs.

11:30 **Lecture**: A. Lagendijk, University of Amsterdam, *Localization of Light: II*

12:30 **Talk**: D. Wiersma, University of Florence, *Propagation of Light in Partially Disordered Systems*

The nematic phase of a liquid crystal is characterized by a global alignment of the molecules in a direction called the nematic director and an otherwise translational disorder. The strong opacity of the nematic phase comes about from local fluctuations of the nematic director that elastically scatter light. The strong scattering combined with the partial ordering of the nematic phase leads to an anisotropic diffusion process. There are several ways of combining nematics with either ordered (photonic crystals) or disordered (porous solids) dielectric structures. We have studied experimentally various aspects of anisotropic light diffusion, amongst which the anisotropy in the diffusion constant by means of time-resolved transmission experiments.

13:00 **Talk:** P. Halevi, Puebla, Mexico, *Homogenization of 2d Periodic Composites and Photonic Crystal Optics*

This talk concerns composite materials that have periodicity in a plane. They are formed by identical, long cylinders that constitute a two-dimensional, arbitrary Bravais lattice in the plane perpendicular to the cylinders. The cross-section of the cylinders is also of arbitrary form. The cylinder material and the intersticial material are assumed to be homogeneous and isotropic. In the last decade, such structures came to be known as photonic orphononic crystals - depending whether the materials involved are of transparent or of elastic nature. The study of these periodic composites usually focuses on a high-frequency band gap - the phononic or photonic gap in which, respectively, light or sound cannot propagate. Here, on the contrary, we are interested in the low-frequency regime, where the wavelength (corresponding to the Bloch vector) is much greater than the lattice spacing. Thus, we present a theory of homogenization applicable to a very general class of composites with two-dimensional periodicity. Our method is applicable to a wide class of materials: dielectric, magnetic, electrically conducting, thermally conducting, etc. For simplicity, the material properties are given in terms of the dielectric constants of the cylinder and host substances.

The homogenization is performed by taking the quasistatic limit of Maxwell's equations. In this limit, we prove that the composite behaves like either a uniaxial or a biaxial (homogeneous)optical medium. That is, it can be described by means of a hermitian dielectric tensor that can be diagonalized. It has three eigenvalues -the Principal Dielectric Constants- that, in general, are all different. We have derived exact and compact formulas for these dielectric constants, given in terms of summations over the two-dimensional reciprocal lattice and a matrix inversion. These formulas have been applied to a variety of Bravais lattices, cylinder cross-sectional shapes, and materials. In each case, the Principal Dielectric Constants are computed as a function of the cylinder filling fraction. Convergence is very rapid, and some of our results are of unprecedented precision.

Evening Session Chairperson: A. Moroz

17:30 **Lecture**: C. Beenakker, Leiden University, *Random Matrix Theory of Random Lasers and Photonic Localization: I*

A random laser differs from a conventional laser in that the feedback is provided by multiple scattering from disorder rather than by confinement from mirrors. The statistical properties of the radiation are strikingly different because the scattering is chaotic (in contrast to integrable scattering in a conventional laser). Random-matrix theory provides a powerful tool for the study of the quantum optics of such chaotic resonators. Because it is a non-perturbative approach, it can deal with the strongly disordered regime in which the photons are localized by the interference of multiply scattered waves. The interplay of localization and stimulated or spontaneous emission is a fascinating new field of research, that is just beginning to be explored.

Tuesday, June 27, 2000

Morning Session Chairperson: M. Sigalas

9:00 **Lecture**: E. Yablonovitch, University of California, Los Angeles, *Electromagnetic Band Gaps at Photonic and Radio Frequencies: II*

10:00 **Lecture**: H. Benisty, Ecole Polytechnique, Palaiseau, *Applications of 2d Photonic Crystals to Optoelectronics: I*

In these lectures, we will start with a brief reminder of basics of semiconductor optoelectronics by addressing the role of heterostructures (not only as diodes but also as guides or Bragg mirrors) in edge-emitting laser, light-emitting diode (LED) and VCSELs. We will classify the different modes in heterostructures through the effective index. We will also introduce the more complex "photonic integrated circuits" which are able to carry out sophisticated treatments of light beams, ideally on a monolithic system. We will then turn to the impact of lower photon dimensionality on spontaneous emission in optoelectronics. The planar microcavity case is interesting to start with, as it is a case of modulation of the DOS in different directions, without much difference of the overall DOS and it is well documented for application to LEDs. Then, the feasibility of single mode emission in a cavity defined in a waveguide and/or in a micropillar defined in a microcavity will be examined in the limit case of negligible " Purcell effect ."

We will next discuss specifically the modelling tools and the properties of 2D PC etched through waveguides. One issue of paramount importance for applications in optolectronic devices is how far these structures can be regarded as ideal 2D ones, i.e. as infinite air rods in a homogeneous matrix. The light line is a basic concept to examine the role of the guide index contrast (3.3:1 in the case of InP-based self-supported membranes and 3.5:3, or less, in the case of conventional substrates). However, the light line is not adapted to discuss the defect modes, which are the only to be used in devices. A complementary perturbative approach based on a separable solution of the etched waveguide will be introduced. It will be shown to provide quite realistic estimates of light losses in various kind of experiments with a single parameter added to the 2D problem. Cavities, which are an essential building-block of various devices, will be used as examples to illustrate possible treatments of these losses.

The last part of these lectures will be devoted to issues in integrated optics : What are the approaches to design a basic PC-based straight guide? What are the technological issues towards large scale? How could coupling be engineered in all-PC structures, e.g. between a PC microcavity and a guide ? How far do the existing tool box and concepts extend? and also what remains to be set up towards optoelectronics applications?

11:30 **Talk:** A. Forchel, Wuerzburg University, *Integration of Photonic Crystals with Active Optoelectronic Devices*

We have investigated the integration of photonic crystal structures with active optoelectronic devices based on ridge waveguide lasers. The photonic crystal is realized by a triangular lattice of air holes etched into the semiconductor. Confinement of the light parallel to the holes is provided by the waveguide of the laser.

An InGaAs/AlGaAs structure with a single InGaAs quantum well emiting at 990 nm in TE polarization (|| QW) is used for laser fabrication. The ridge waveguide is etched to a distance of 150 nm from the GaAs waveguide layer. Electron beam lithography is then used to define a triangular array of holes with lattice constants between 160 and 400 nm in PMMA resist. The pattern is etched in an intermediate metal mask and finally transferred into the semiconductor.

12:00 **Talk:** R. B. Wehrspohn, Max-Planck Institute of Microstructure, Halle, *Electrochemically Prepared High-aspect-ratio Pore Arrays for 2d Photonic Crystal Applications*

Formation and characterization of two-dimensional arrays of pores with very high aspect ratios based on anodic etching of silicon and aluminum will be described. Regular pattern formation by self-organization and by lithographic techniques will be dealt with. In both cases, these pore arrays can be used as two-dimensional photonic crystals, which exhibit an optical bandgap from the infrared to the visible depending on the anodization conditions. Diverse defect structures can be easily introduced by lithographic prepattering. For example wave-guides as well as microcavities have been fabricated and characterized optically.

Evening Session Chairperson: E. Yablonovitch

17:30 **Lecture**: T. F. Krauss, University of St. Andrews, *Patterned Photonic Crystal Waveguides: II*

I will review the development of semiconductor-based planar photonic crystals, highlight the underlying concepts, materials and fabrication issues and point towards important issues for device applications. Examples of successful photonic crystal-based devices include photonic crystal waveguides and photonic integrated circuit elements as well as lasers and LEDs.

18.30 **Panel Discussion**: *Applications of Photonic Band Gap*

Wednesday, June 28, 2000

Morning Session   Chairperson: H. Benistry

9:00 **Lecture**: C. Beenakker, Leiden University, *Random Matrix Theory of Random Lasers and Photonic Localization: II*

10:00 **Talk:** Zhao-Qing Zhang, Hong Kong, *Photonic Crystals and Perturbation Theory*

We show here, with three examples, that a simple perturbative approach is very useful to understand certain photonic band gap problems. In the first example, we will demonstrate that the perturbation analysis can provide us a simple, systematic and efficient way to engineer a photonic band gap. The change of a gap size caused by the variation in the microstructure can be easily determined from the knowledge of eigenfield distribution at two band edge states. Thus, by knowing the field distribution at some symmetry points, one should be able to manipulate an existing gap by changing its microstructure. Explicit examples are given for certain 2D photonic crystals where full/absolute gaps are enlarged significantly. By extending this perturbation analysis to a disordered photonic crystal, in the second example, we explain why a gap is more robust against positional disorder of the scatterers and more sensitive to the randomness in the size of the scatterers. Specific examples are presented for some 2D and 3D photonic crystals. In the final example, we will use the various eigenfield distributions to explain why an incomplete infiltration has a larger photonic gap in an inverse opal photonic crystal. By careful mode analysis, we see that the enlargement of the photonic band gap due to incomplete infiltration ininverse opal is the result of subtle changes in the photonic bands at two particular k-points in the Brillouzin zone due to the depletion of high dielectric material.

10:30 **Talk:** Y. Vlasov, Ioffe Institute, *Influence of Disorder in Photonic Crystals*

Self-organized synthetic opals possessing a face centered cubic fcc lattice are promising for fabrication of three-dimensional photonic crystal with a full photonic band gap in the visible. The fundamental limiting factor of this method is the large concentration of lattice defects and, especially, planar stacking faults, which are intrinsic to self-assembling growth of colloidal crystal. On the other hand this makes synthetic opals an ideal model system for the studies of the effects of disorder on photonic band structure. We have numerically analyzed the mechanisms of light localization in such a periodic-on-average system with variable amount of disorder. It is known that photonic Bloch states can become strongly localized near the bandedges in a disordered photonic crystal. We show that Bloch states are disrupted and the new localization regime establishes when local fluctuations of the bandedge frequency caused by randomization of refractive index profile becomes as large as the bandgap width. This results in strong inhomogeneous broadening of the photonic stopbands in experimental reflection and transmission spectra. Transmission experiments performed on opal photonic crystal have shown the exponential decay of light throughout the gap region, which is ascribed to building up of this second regime of light localization.

11:30 **Talk:** C. M. Soukoulis, Ames Laboratory, Iowa State University, *The Effects of Disorder in Photonic Band Gap Structures*

By using two ab initio numerical methods we study the effects that disorder has on the spectral gaps and on wave localization in two-dimensional photonic band gap materials. We find that there are basically two different responses depending on the lattice realization (solid dielectric cylinders in air or vise versa), the wave polarization, and the particular form under which disorder is introduced. Two different pictures for the photonic states are employed, the "nearly free" photon and the "strongly localized" photon. These originate from the two different mechanisms responsible for the formation of the spectral gaps, ie. multiple scattering and single scatterer resonances, and they qualitatively explain our results.

12:00 **Talk:** V. Kuzmiak, Chez Republic, *The Localization of Light in a Random 2d Dielectric Medium*

We systematically study the strong localization of the light in a two-dimensional, randomly disordered, dielectric medium, that is periodic in average. We consider a simple scattering geometry consisting of an infinite array of infinitely long, parallel, dielectric rods of square and circular cross section embedded in a vacuum. In the case of the parallel rods of square cross sections the dielectric constant of each rod is independent random variable whose values are uniformly distributed about an average value ϵ_a. In systems formed by the rods of circular cross section the disorder is introduced by statistically uncorrelated dielectric constant of each rod, positions of the scatterers and radius of each rod all of which are small deviations satysfying a gaussian probablity distribution. We calculate photonic band structure of average periodic system. and by using finite-difference time-domain methods based on the numerical excitation of the mode by virtual oscillating dipole embedded in the center of the computational domain we evaluate the electromagnetic energy stored in consecutive pairs of cylinders centered at the position of the dipole. By inspecting the time-averaged energy associated with the modes with the frequencies close to the band gap edge we observe the strong localization characterized by an exponential decay. We simultaneously calculate the optical transmission of a slab of disordered 2D systems to show the correspondence between the Anderson localized wave functions and the resonances in energy transfer to the transmitted Bragg waves.

12:30 **Talk:** G. Cwilich, Yeshiva University, *Photonic Crystals and Light Localization*

The propagation of a signal in a disordered or a periodic structure is considered in a simple model that contains, as limiting cases, both the propagation of a classical persistent random walker AND the coherent propagation of a wave in the presence of elastic scatterers of mesoscopic physics. A complete statistical analysis of the problem is performed by using a loop-expansion of all the possible paths in a one-dimensional system; the statistics of the distribution of the length of the paths is presented and the transition from the ballistic to the diffusive regime is discussed. A combination of "strip-techniques" allows to generalize this analysis to higher order dimensional systems, for different boundary conditions, and to obtain reflection and transmission coefficients. In particular results for propagation in small N x M structures will be presented, showing the presence of band gaps. The possible application to simple imaging problems will be discussed. The different roles of the "randomness" in the underlying statistical model and the disorder of the medium and their interaction will be discussed, both analytically and through numerical simulations.

12:45 **Talk:** S. Venakides Duke University, *Computational and Theoretical Results in Photonic Crystals*

(a) We compute the transmission properties of 2-d electromagnetic TM waves that are normally incident on a Fabry-Perot structure with mirrors consisting of photonic crystals. We use a boundary integral formulation with quadratic boundary elements and utilize the Ewald representation for the Green's functions. We trace the frequencies of the Fabry-Perot cavity modes traversing the photonic bandgap as the cavity length increases and calculate corresponding Q-values. We do the computation with both lossy and lossless materials. Our results are in very good agreement with experiments performed by H. Everitt's group at Duke.

(b) We derive theoretically Second Harmonic Generation in an LC circuit chain with nonlinear inductors and with capacitors that alternate in value along the chain. We use this as a discrete model of a one-dimensional photonic crystal. The periodicity in the chain is used to achieve phase matching.

Evening Session Chairperson: P. Halevi

17:30 **Talk**: R. Biswas, Ames Laboratory, Iowa State University, *Antenna Applications of Photonic Crystals*

Three-dimensional photonic band gap crystals are utilized to tailor the radiation patterns of antennas. By utilizing the resonances of a Fabry Perot cavity formed with photonic band gap crystals, we were able to create uniquely directional antennas by placing antennas within such cavity. Very good agreeement was obtained between finite difference time domain (FDTD) simulations and measurements. Exceptionally directional patterns over narrow frequency ranges were obtained, with half power beam widths less than 10 degrees were obtained. We will compare the theoretical performance of 3-D and 1-D photonic crystals.

These recent results will be compared with past configurations where dipole antennas were placed on top of photonic crystals and the reflecting properties of the PBG crystals were used to improve antenna performance. Such directional promise several new applications.

18:00 **Talk:** M. Sigalas, Agilent Laboratories, *Waveguide Bends in 3D Layer-by-Layer Photonic Band Gap Materials*

Using finite difference time domain (FDTD) simulations, we study waveguide configurations in a three dimensional layer-by-layer photonic crystal. We study waveguides lying in the plane of the rods. These can be created by removing one or more rods from one layer and the wave is propagating along the removed rods. An L-shaped waveguide is created by removing part of a rod in one layer and part of a rod in the next layer. The removed rods are perpendicular to each other. We found that 100 % transmission efficiency can be achieved through the 90^{o} bend. Also, waveguides created by removing a whole or a part of a rod from each unit cell along the stacking direction have been studied. In that case the wave is mainly concentrated around the defects. The overlap of the wavefunction of neighboring defects allows the propagation of the wave.

18:30 **Talk**: N. A. Nicorovici, University of Sydney, *Localization and Homogenization in Photonic Crystals*

We describe a new method which allows us to investigate photonic crystals modelled as stacks of gratings consisting of metallic, circular cylinders. Our formulation enable us to compute photonic band diagrams of two- and three-dimensional arrays of inclusions and to estimate accurately the edges of the band gaps in the case of lossless materials. In turn, this provides useful estimates of the gap edges for lossy materials. The technique, which is applicable to structures whose layers do not interpenetrate (thereby permitting the use of plane wave expansions for fields between layers) has, at its heart, an eigenvalue problem which is derived by applying a quasi-periodicity condition. The resulting dispersion relation (which involves the scattering matrices of the single representative layer) can then be reduced to an algebraic eigenvalue problem. The solutions of the eigenvalue equation also provide a generalised technique to determine the field modes of the structure. We note that our technique is intrinsically more stable than similar methods as it avoids the inversion of particular scattering matrices, the condition or stability of which cannot be guaranteed. Also, the accuracy of the method is not affected by the high contrast between the cylinders and the surrounding medium. We use the reflection and transmission scattering matrices of a single grating, to generate the corresponding scattering matrices for a finite stack of gratings, and demonstrate closed form expressions for solutions of the recurrence relations. By considering the limit as the stack length increases without bound, we calculate the reflection scattering matrix R¥, which is the fixed point of the recurrence relation for the reflection scattering matrices. By means of R¥ it should be possible to define an effective permittivity at general points in the Brillouin zone. In the quasistatic limit, we obtain an effective permittivity identical to that obtained using the electrostatic theory.

The method can be applied to the study of both ordered and disordered photonic crystals, and can yield analytic insights into problems such as localization and homogenisation. At long wavelengths, the individual grating layers homogenise and the structure behaves as a one-dimensional stack in which Anderson localization of waves is evident, until the wavelength is sufficiently large so as to render the crystal homogeneous. This method can also be generalized to coated cylinders and to crossed stacks with rotation of layers (one layer to the next). A particular choice of crossing angles of 0° and 90° produces approximate polarization insensitivity.

19:00 **Talk:** A. Orlowski, Warsaw, *From Proximity Resonances to Anderson Localization: Universality Effects in Multiple Scattering*

Multiple elastic scattering of both scalar and electromagnetic waves from a collection of randomly distributed objects is studied. Novel universal properties of the spectra of random Green matrices involved in the description are discovered. A striking physical interpretation within various models of the single scatterer is elaborated. Proximity resonances and Anderson localization are considered as two illustrative examples. Generalizations of 2D numerical transmission experiments are also given.

Thursday, June 29, 2000

Morning Session Chairperson: T. F. Krauss

9:00 **Lecture**: H. Benisty, Ecole Polytechnique, Palaiseau, *Applications of 2d Photonic Crystals to Optoelectronics: II*

10:00 **Talk:** D. Chigrin, University of Wuppertal, *One-Dimensional Photonic Crystals: Omnidirectional Reflection and Superprism Phenomena*
A review on photonic bandgap related phenomena in the simplest type of photonic crystals, i.e., one-dimensional (1D) periodic structures, will be presented. The main focus will be on the omnidirectional reflection and superprism phenomena displayed by 1D photonic crystals. Possibilities to design optoelectronic devices based on these phenomena, e.g., laser microcavities, hollow fibers, collimators, and prisms, will be specifically addressed.

10:30 **Talk:** A. Moroz, Ultrech University, *Complete Photonic Band Gap Structures Below Infrared Wavelengths*
Till recently, no two- and three-dimensional structures have been known to yield a practical complete photonic bandgap (CPBG) for refractive indices available below infrared wavelengths, mainly because of the simultaneous requirements on the dielectric contrast and the modulation (the total number and the length of periodicity steps).We show a promising new route to achieve a CPBG below the infrared wavelengths, using a periodic arrangements of scatterers of material with Drude-like behavior of the dielectric function. In two-dimensions, for a simple square lattice several CPBG's open and a relative gap width g_w (gap width to the midgap frequency ratio)can be as large as 34 even if the host dielectric constant $\varepsilon_h=1$. In three-dimensions, despite of recent claims, simple face-centered-cubic (fcc) structures of spheres are shown to yield a tunable CPBG in the region from GHz down to optical wavelengths using currently available experimental techniques. Up to four CPBG's can open in the frequency region $0.6\ \omega_0 \le \omega_l \le \omega_p$ with ω_p being the plasma frequency, where the sphere material bulk absorption is assumed to be small (a nonabsorptive window). The relative gap width g_w can be as large as 10 even if the host refractive index $n_h=1$. These properties are rather robust against coating of such spheres with a semiconductor or an insulator. Using different coatings and supporting liquids, the width and midgap frequency of a CPBG can be tuned considerably. These results open a door to fabrication of CPBG structures in the visible using colloidal crystals. In the latter case, CPBS's can be switched on and off by applying an electric field, since the latter allows to switch in ms from an fcc colloidal crystal to a body centered tetragonal (bct) crystal: a so-called martensitic transition.

11:30 **Lecture**: E. Yablonovitch, University of California, Los Angeles, *Electromagnetic Band Gaps at Photonic and Radio Frequencies: III*

Evening Session Chairperson: C. M. Soukoulis

17:30 **Remarks and Discussion**: *Open and Future Directions*

18:00 **Panel Discussion**: *Open and Future Directions*

19:30 **Closing Session**: End of the Institute

Poster Presentations

P1	**Mario Agio**, University of Pavia, Pavia, Italy	Impurity modes in a photonic crystal: coupling efficiency and quality factor
P2	**Ivan Alvarado-Rodriguez**, UCLA Optoelectronics, Los Angeles, CA	Photonic crystal defect cavities in InGaAs
P3	**Richard Amos,** DERA, United Kingdom	Fabrication of large-are colloidal crystals using one- and two-dimensional shear
P4	**Dimitris Angelakis**, Imperial College, London, United Kingdom	Coherent effects in two band photonic crystals
P5	**Vasily Astratov**, University of Sheffield, United Kingdom	Direct study of heavy photon dispersions in photonic crystal waveguides
P6	**Mark Auslender**, Ben-Gurion University of the Negev, Israel	On the correct use of plane-wave discretization in photonic-structure simulation: Grating diffraction example
P7	**Mehmet Bayindir**, Bilkent University, Ankara, Turkey	Propagation of photons through localized coupled-cavity modes in photonic band gap structures
P8	**Mona Berciu**, University of Toronto, Canada	Theory of fluorescence in three-dimensional photonic crystals
P9	**Navin Bhat,** University of Toronto, Canada	Optical pulse propagation in nonlinear photonic crystals
P10	**Alvaro Blanco**, Instituto de Ciencia de Materiales de Madrid, Madrid, Spain	Photonic properties of CdS inverted opals
P11	**Muriel Botey Cumella**, Universitat Politecnica de Catalunya, barcelona, Spain	Momentum nonconserving interactoin within a layer of nonlinear material localized in a subwavelength region of the space
P12	**Niclas Carlsson**, FESTA, Ibaraki, Japan	Formation of 2D photonic crystal airbridge structures in AlGaAs based semiconductor heterostructures
P13	**Martin Charlton,** University of Southampton, United Kingdom	Analysis of photonic crystal waveguide devices
P14	**Crina Maria Cojocaru**, Universitat Politecnica de Catalunya, Barcelona, Spain	Dispersive properties of a truncated 1-dimensional photonic crystal
P15	**M. Cornelia Cuisin**, Institut d'Electronique fondamentale, Orsay, France	PMMA resist templates for dielectric and metallic "Yablonovite" photonic crystals at submicrometer scales
P16	**Michiel de Dood**,FOM, The Netherlands	Fabrication and optical doping of 1, 2, and 3-dimensional photonic materials using ion beams
P17	**George Deligeorgis,** FORTH, Crete, Greece	Application of reactive ion etching for GaAs-based integrated optoelectronics
P18 P19	**Ihab El-Kady**, Iowa State University, United States	Waveguides in two-dimensional photonic band gap structures Metallic photonic crystals at optical wavelengths
P20	**Stefan Enoch**, Faculté des Sciences et Techniques de St. Jérome, Marseille, France	Anomalous refractive properties of photonic crystals at the band edges
P21	**Nayer Eradat**, University of Utah, United States	Optical studies of metal infiltrated opal photonic crystals
P23	**Alexei Erchak**, Massachusetts Institute of Technology, Cambridge, MA, U.S.A.	Increased light extraction from a light-emitting diode using a two-dimensional photonic crystal
P23	**Jan Fagerstrom**,FOA, Sweden	Characterization of a three-dimensional microwave photonic crystal
P24	**Lucia Florescu**, University of Toronto, Canada	Time-dependent diffusion model of lasting in a random amplifying medium
P25	**Marian Florescu**, University of Toronto, Canada	Non-Markovian atomic switching in photonic band gap materials
P26	**Eliane Flück**, University of Twente, The Netherlands	Light interference in waveguides containing periodic one-dimensional air rod arrays
P27	**Stavroula Foteinopoulou**, Iowa State University, United States	Tight Binding Parametrization of Photonic Crystals
P28	**Valentin Freilikher**,Bar-Ilan University, Israel	Transport and localizations in quasi-one-dimensional systems
P29	**Antonio Garcia-Martin**, Universidad Autonoma de Madrid, Spain	Conductance distributions and transport eigenchannels: From conductance quantization to Anderson localization
P30	**Florencio Garcia Santamaria**, Universidad Autonoma de Madrid, Spain	Photonic properties of CdS inverted opals
P31	**Jacek Generowicz**, University of Southampton, United Kingdom	Modelling photonic crystals using finite elements
P32	**Cécile Goffaux**, Laboratoire de Physique du Solide, FUNDP, Namur, Belgium	Acoustic and elastic waves propagation in two and three dimensional periodic heterostructures
P33	**Jaime Gomez Rivas**, Van der Waals-Zeeman Instituut, Amsterdam, The Netherlands	Optical experiments on germanium powders close to the Anderson localization transition
P34	**Raquel Gomez-Medina**, Universidad Autonoma de Madrid, Spain	Enhanced electromagnetic field-particle interactions in a waveguide

P35	**Serguei Grabtchak**, University of Toronto, Canada	Self-assembly of 3-D PBG materials
P36	**Boris Gralak**, Faculté des Sciences et Techniques Centre de Saint Jérome, France	Transmission by photonic crystals: unbounded transfer operators approach
P37	**Zhong-Ze Gu**, Kanagawa Academy of Science and Technology, Japan	Control of photonic band structure by photo-irradiation
P38	**Christian Hermann**, Institute of Technical Physics, Germany	Lightfield propagation in 2D photonic crystal slab waveguide structures
P39	**Reinald Hillebrand**, Max Planck Institute of Microstructure Physics, Halle, Germany	Theoretical study of complete photonic band gaps for varying 2D filling patterns of oval-shaped type
P40	**Marta Ibisate**, Instituto de Ciencia de Materiales de Madrid (CSIC), Madrid, Spain	Photonic properties of CdS inverted opals
P41	**Arnout Imhof**, Van der Waals-Zeeman Instituut, University of Amsterdam, The Netherlands	Diffusive and coherent transport of light in strongly scattering porous GaP
P42	**Steven Johnson**, Massachusetts Institute of Technology, United States	Photonic crystals in 3D planar structures and integrated optics
P43	**Maria Kafesaki**, University of Crete, and FORTH, Crete, Greece	Band gaps phenomena in twinned periodic elastic composites
P44	**Robin Kaiser**,INLN, France	Coherent backscattering of light by laser cooled atoms
P45	**Erik Knudsen**, Technical University of Denmark, Kgs. Lyngby, Denmark	Waveguiding properties of photonic crystal fibres
P46	**Femius Koenderink**, University of Amsterdam, The Netherlands	Enhanced backscattering from photonic crystals
P47	**Patrick Kramper**, Universitaet Konstanz, Germany	Spectroscopy of defect modes in photonic crystals
P48	**Sissy Kyriazidou**, University of California--Los Angeles, United States	Fundamental electromagnetic excitation of PBG materials: A formal analogy of PBG and natural crystals
P49	**Miguel Laso**, Publi University of Navarre, Spain	Photonic crystals in microstrip technology
P50 P51	**Ralk Lenke**, University of Konstanz, Germany	Magnetic Field Effects on Coherent Backscattering in case of Mie Scattering Comparison between the `The Glory' and Coherent Backscattering of Light in turbid Media
P52	**Stephen Leonard**, University of Toronto, Canada	Two-dimensional single-mode photonic crystal waveguides fabricated in silicon
P53	**Marine Levassor d'Yerville**, Universite Montpellier, France	Influence of defect positions on the diffraction properties of photonic crystals
P54	**Txema Lopetegi**, Universidad Autonoma de Madrid, Spain	Vacancy lattices in two-dimensional acoustic crystals
P55	**Fernando López-Tejeira**, Universidad Autonoma de Madrid, Spain	Diffraction effrects in artificial opals
P56	**Virginie Lousse**, ;Facultés Universitares Notre Came de la Paix, NamurBelgium	Influence of illumination on the density of modes of photorefractive nonlinear photonic crystals
P57	**Torsten Maka**	Thin film photonic crystals
P58	**Vinothan Manoharan**, University of California--Santa Barbara, United States	Ordered macroporous ritile titanium dioxide by emulsion templating
P59	**Jesus Manzanares Martinez**, Université Montpellier II, France	Photonic defect states in imperfect coated opals
P60	**Luis Martin-Moreno**, Universidad de Zaragoza, Spain	Self-Assembled triply periodic minimal surfaces as moulds for photonic band gap materials
P61	**Beatriz Martinez**, Public University of Navarra, Spain	Patch antenna design with a photonic bandgap substrate
P62	**Hernan Miguez**, la Universidad Politecnica de Valencia, Valencia, Spain	Photonic properties of CdS inverted opals
P63	**Daniel Mittleman**, Rice University, United States	Using colloidal crystals as templates for the formation of novel photonic materials
P64	**Jessica Mondia**, University of Toronto, United States	Tunable two-dimensional photonic crystals using liquid crystal infiltration
P65	**Maria Caterina Netti**, University of Southampton, United Kingdom	2D photonic crystal waveguides: Band gaps and light cones
P66	**Bianca Nelson,** University of Stanford	A periodic dielectric stack as a one-dimensional photonic crystal for wavelength demultiplexing by beam shifting
P67	**Georgios Nikolopoulos**, University of Crete, Greece	Beyond single-photon localization at the edge of a photonic band gap
P68	**Ségolène Olivier**, Ecole Polytechnique, Palaiseau Cedex, France	Optical properties of photonic crystal straight waveguides
P69	**Raluca Penciu**, University of Crete, Greece	Vibrational modes in solution of copolymers

P70	**Suresh Pereira**, University of Toronto, Canada	Canonical quantization of envelope function equations in a PBG material
P71	**David Peyrade**, Université Montpellier, France	GaN 2D photonic crystals
P72	**Felipe Pinheiro**, Centro Brasileiro de Pequisas Fisicas, Brasil	Multiple scattering of light in disordered magnetic media: Localization parameter, transport velocity and diffusion constant
P73	**Luca Plattner**, University of Southampton, United Kingdom	Advances in modelling of *Morpho*-type diffracive structures
P74	**Vladimir Poborchii**, National Institute for Advanced Interdisciplinary Research, Japan	Photonic-band-gap properties of 2-dimensional lattices of Si nanopillars
P75	**Iounnis Psarobas**, University of Athens, Greece	A layer Korringa-Kohn-Rostoker method for phononic crystals
P76	**Min Qiu**, Royal Institute of Technology, Sweden	Studying photonic band-gap structures by finite-difference time-domain method
P77	**Rajesh Rengarajan**, Rice University, United States	Controlling the optical band gap properties of macroporous polymers by the application of mechanical compression
P78	**Andrew Reynolds**, Glasgow, Scotland, United Kingdom	Analysis of membrane support structures for integrated antenna usage on 2-dimensional photonic band gap structures
P79	**Jorge Ripoll**, ICMM, Spain	Multiple layered diffusive media: Theory and experiments
P80	**Andrey Rogach**, University of Hamburg, Germany	Chemical route to three-dimensional colloidal photonic crystals doped with semiconductor nanoparticles
P81	**José Sanchez-Dehesa**, Universidad Autonoma de Madrid, Spain	Vacancy lattices in two dimensional acoustic crystals
P82	**Juan Vicente Sanchez-Perez**, Universidad Politecnica de Valencia, Spain	Experimental and theoretical determination of acoustic dispersion relations in two-dimensional systems
P83	**Jorg Schilling**, Max-Planck-Institut for Microstructure Physics, Halle, Germany	Photonic crystals made of macroporous silicon: Down to near IR, up to 3 dimensions
P84	**Serguei Skipetrov**	Temporal fluctuations and instabilities of waves in nonlinear disordered media
P85	**David Taylor**, DERA, United Kingdom	Colloidal crystals in a liquid crystal host
P86	**Burak Temelkuran**, Bilkent University, Turkey	Silicon micromachined quasi-metallic photonic crystals
P87	**Victor Tikhomirov**, University of Leeds, United Kingdom	High refractive index chalcogenide glasses for photonic band-gap devices
P88	**Adriaan Tlp**, FOM, The Netherlands	Band structure for absorptive photonic crystals
P89	**Ovidiu Toader**, University of Toronto, Canada	Photonic crystals exhibiting full photonic band gaps
P90	**Han van der Lem**, FOM, AMOLF, The Netherlands	Two-dimensional Complete Photonic-Bandgap Structures in the Visible
P91	**Jerome Vasseur**, Universite de Lille, France	Defect mode in one-dimensoinal combined photonic waveguides--application to the resonant tunneling between two continua
P92	**Krassimir Velikov**, Utrechyt University, The Netherlands	Photonic crystals from core-shell colloidal particles
P93	**Jean-Pol Vigneron**, Facultes Universitaires Notre Dame De La Paix, Belgium	Tight-binding description of polarization waves in periodic arrays of metal dots
P94	**Joachim Wagner**, Universität des Saarlandes, Germany	Preparation of Mesoscale Ordered Structures by Means of Immobilized Colloidal Crystals
P95	**Vassilos Yannopapas**, NTVA, Greece	Effect of moderate disorder on the absorbance of plasma spheres distributed in a host dielectric medium
P96	**Ji Zhou**, Nanyang Technological University, Singapore	Three-dimensional photonic bandgap structure of a polymer-metal composite
P97	**Majd Ellas Zoorob**, University of Southampton, United Kingdom	Investigation into very highly symmetric photonic quasicrystals based on the pinwheel quasicrystal lattice structure

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